REMARKS

Claims 1-27 have been examined. Claim 24 has been cancelled without prejudice or disclaimer. Claims 1-23 and 25-27 are all the claims pending in the application.

Petition to Make Special

Applicant respectfully notes that a Petition to Make Special was submitted on September 28, 2005. However, Applicant has received no acknowledgment or decision on the Petition. Therefore, Applicant respectfully requests the Examiner to acknowledge the Petition to Make Special and grant the applicant appropriate consideration under the Petition.

Formal matters

The disclosure is objected to because the specification refers to color drawings to illustrate the invention, but the drawings submitted are in black-and-white. Applicant herewith submits eight (8) sheets of color drawings and the required Petition Under 37 C.F.R. § 1.84. Thus, Applicant respectfully requests that the objection to the specification be removed.

The drawings are objected to as failing to comply with 37 C.F.R. § 1.84(p)(5) because they do not include reference character 38 which is mentioned in the specification at page 12, line 27. Applicant herewith submits a new drawing sheet showing Fig. 1b, where reference designator 38 is depicted, and thus respectfully requests the Examiner to remove the objection.

The drawings are also objected to under 37 C.F.R. § 1.83(a) because the drawings must show every feature of the invention specified in the claims. Specifically, the Examiner lists a number of features which are not shown: a collimating block with collimating slots; fan-shaped

beams; a detector collimator; a computing means; a display means; a second neutron source; crossed wavelength shifting fibers; different colored pixels; multiple sets of detectors; a mask; and reflective surfaces.

Applicant herewith submits 16 sheets of replacement drawings and 4 sheets of new drawings showing these features. Specifically,

- Figure 1 (now referenced as Fig. 1a) has been amended to include reference to the computer means 15 and display means 25.
- Additional figure 1b has been added to illustrate the source and detector collimating slots respectively referenced 38 and 39.
- Additional figure 1c has been added to illustrate the fan shaped radiation beam.
- Figure 2 (now referenced figure 2a) has been amended to include reference to the mask 31 as claimed in claim 27.
- Additional figure 2b has been added to illustrate the reflective surface of the mask as claimed in claim 27.
- Additional figure 2c has been added to illustrate the alternate detector array as claimed in claim 12.
- Figures 3, 4, 8a and 8b, 9a and 9b, 10a and 10b, and 11 remain unchanged.
- Figures 5a and 5b, 6a to 6c, 7a to 7c, 8c and 8d, 9c and 9d, 10c and 10d, 12a to 12e and 13a to 13c have been replaced with colour representations.
- Additional figure 14 has been added to illustrate the second energy source (dual energy embodiment).

With regard to the reference to the 'multiple sets of detectors', claim 24 has been deleted.

In addition, line 26 of page 11 of the specification has been amended to clarify that the collimating block which surrounds the neutron and x-ray/gamma-ray sources is in the form of a source shield housing 16.

The feature of the "different colour pixels" of claims 13-14 is shown in the drawings represented by figures 5 to 10. Moreover the specification states on page 11, line 31 to 32 that "the radiation receiving area of each scintillator rod 19 corresponds to a single pixel in the

image-frame." It is then stated on line 34 of page 14 to line 6 of page 15 that: "the results from six scans are shown in figures 5 to 10 ... The colour of a pixel corresponds to the R value for that pixel, with lower R values coloured blue, intermediate values turquoise through green to yellow and higher values orange."

Applicant herewith also submits a Substitute Specification amended to reference the additional drawings and to add the language required by 37 C.F.R. § 1.84 for color drawings. Applicant therefore respectfully requests that the Examiner remove the objection to the drawings and accept the drawings on the next action.

At page 3 of the Office Action, the Examiner objects to the listing of references in the specification on pages 22-23 -- that the list is not a proper information disclosure statement. On October 6, 2006, Applicant submitted these documents on form PTO-892 in an Information Disclosure Statement. Therefore, Applicant respectfully requests the Examiner to grant the documents required consideration.

Claim objections

Claims 1-27 stand objected to for various informalities with respect to antecedent basis, functional or operation language, and grammatical error. Applicant has amended the claims as suggested by the Examiner, and therefore respectfully requests that the objections be removed.

Claim rejections -- 35 U.S.C. § 112

Claims 1-27 stand rejected under 35 U.S.C. § 112, second paragraph, as allegedly indefinite. Applicant has amended the claims as suggested by the Examiner.

With further regard to claims 4-6, Applicant respectfully submits that the attached drawing figures address the Examiner's concerns.

With further regard to claims 1 and 8, Applicant respectfully submits that one having ordinary skill in the art would understand the meaning of the term "or similar." Specifically, the term, "or similar" in the context of the claim and the disclosure in the specification, would be readily understood by one having ordinary skill in the art. As noted at MPEP § 2173.05(b), the fact that relative terminology may not be precise does not automatically render the claim indefinite. The acceptability of the claim language depends on whether one of ordinary skill in the art would understand what is claimed in light of the specification.

Applicant hereto attaches, as indicative of the common general knowledge regarding sealed-tube generators, an excerpt from the "Handbook of Fast Neutron Generators" (CRC Press, Inc, 1987), which explains the characteristics of sealed-tube generators on page 98, including their principal advantages and typical values of their operational voltages (i.e. "at 100 to 200 kV"). One having ordinary skill in the art would thus understand, in the context of the application (relating principally to systems for imaging cargo and the like) and the described disadvantages of the related art, that "a sealed-tube or similar generator for producing the neutrons" means either a sealed-tube generator or a neutron generator that is similarly

inexpensive, compact, easy to operate and with low operating voltages of around 80–200 kV (cf. the range given by the "Handbook of Fast Neutron Generators" and the specific example given on page 11 line 17 of the specification).

Applicant respectfully submits, therefore, that the term "sealed-tube or similar generator for producing the neutrons" is restrictive in a manner that would be readily understood by one having ordinary skill in the art.

Applicant also respectfully submits that it would also be understood that, in this art, there is a limited number of methods for generating "mono-energetic fast neutrons" by the "D-T or D-D fusion reactions" that the skilled person would contemplate as in any way useful. Applicant refers the Examiner to the paper: "A review of neutron based non-intrusive inspection techniques" by T. Gozani published by the Hoover Institution in March 2002. In the paper, Gozani itemizes—in Table 3—what he regards as all viable alternatives, from those that have "compelling technical and operational merits" to others that "may be no more than interesting exercises in applied nuclear physics" (see Gozani, page 3 lines 22 and 23, enclosed). Table 3 contains only nine broad techniques, each of which the author characterizes—presumably satisfactorily for the skilled person—in simple terms. With so few techniques available, Applicant respectfully submits that it is a simple matter for one having ordinary skill in the art to determine whether any specific approach is comparable to any other specific approach.

It should be remembered that the source of claim 1 may be paraphrased as "a sealed-tube generator for producing substantially mono-energetic fast neutrons via the D-T or D-D fusion

reactions or a similar generator for producing substantially mono-energetic fast neutrons via the D-T or D-D fusion reactions"; this definition is at least as detailed as the definitions used by Gozani and—like Gozani's definition—is sufficient to allow one having ordinary skill in the art to determine whether or not any particular source falls within it.

Applicant thus submits that the expression "or similar"—employed by the inventors and adopted in the drafting of claim 1—has clear bounds that would be readily understood by the skilled addressee. In this regard, Applicant further submits that the term "where the X-ray or gamma-ray source comprises a ^{137}Cs, ^{60}Co or similar radioisotope source having an energy of substantially 1MeV" may be paraphrased as "where the X-ray or gamma-ray source comprises a ^{137}Cs source or ^{60}Co source having an energy of substantially 1MeV or a similar radioisotope source having an energy of substantially 1MeV" and is thus restrictive in a manner that would be readily understood by skilled addressee.

Claim rejections -- 35 U.S.C. § 102

Bartle

Claims 1-4, 11, 13, 15, 17, 18, 20, 22, 24, and 26 stand rejected under 35 U.S.C. § 102(b) as allegedly being anticipated by U.S. Patent No. 5,479,023 to Bartle. Applicant respectfully traverses this rejection.

In order for the Examiner to make a prima facie rejection under 35 U.S.C. § 102, the applied references must disclose all the elements of the invention as claimed. ("A claim is anticipated only if each and every element as set forth in the claim is found, either expressly or

inherently described, in a single prior art reference." *Verdegaal Bros. v. Union Oil Co. of California*, 814 F.2d 628, 631, 2 USPQ2d 1051, 1053 (Fed. Cir. 1987). "The identical invention must be shown in as complete detail as is contained in the ... claim." *Richardson v. Suzuki Motor Co.*, 868 F.2d 1226, 1236, 9 USPQ2d 1913, 1920 (Fed. Cir. 1989)). See also MPEP § 2131.

Claim 1 recites the feature of "*a first neutron source of substantially mono-energetic fast neutrons produced via the deuterium-tritium or deuterium-deuterium fusion reactions, comprising a sealed-tube or similar generator for producing the neutrons.*" It is respectfully submitted that Bartle does not teach, nor suggest, the use of mono-energetic neutron sources comprising a sealed-tube or similar generator for producing the neutrons.

Furthermore claim 1 recites the feature of "*a collimating block surrounding the neutron and X-ray or gamma-ray sources, comprising one or more slots for emitting substantially fan-shaped radiation beams*". The Examiner maintains that this feature is met by Bartle at column 2 lines 61 to 64 and column 3 lines 17 to 40. Applicant respectfully disagrees. At the cited portions, Bartle discloses that the sources of radiation are preferably obtained from a radio-active isotopic source and describes the general operation of Bartle's device i.e., that the neutron and gamma radiation are simultaneously transmitted through a container and then analyzed to determine different materials. However, these cited portions of Bartle do not disclose a collimating block surrounding both sources, do not disclose one or more slots for emitting the radiation, and do not disclose fan-shaped beams.

Additionally, claim 1 recites the feature of "*a detector array comprising a multiplicity of individual scintillator pixels to receive radiation energy emitted from the sources*". The

Examiner maintains that his feature is met by detection unit 5 of Bartle and the disclosure at column 5 lines 31 to 43. However, Bartle does not disclose that the detection unit 5 is in the form of an array. Moreover, at lines 31 to 43 of column 5, Bartle mentions using scintillation detectors, but the scintillators are in a cell 15 cm in thickness. Thus, Bartle does not disclose individual scintillator pixels, as set for by the claim.

For these reasons, claim 1 is not anticipated and therefore is patentable over Bartle. It is respectfully submitted that the remaining claims are patentable, at least, based on their respective dependencies.

Gozani

Claims 1, 3, 7, 13, 15, and 17-21 stand rejected under 35 U.S.C. § 102(b) as allegedly being anticipated over U.S. Patent No. 5,098,640 to Gozani.[1] Applicant respectfully traverses this rejection.

As amended, claim 1 explicitly claims "*a first neutron source of substantially mono-energetic fast neutrons ...*" and "*a separate source of X-rays or gamma-rays of sufficient energy to substantially penetrate an object to be imaged*". In contrast, the neutron source taught by Gozani produces pulsed fast neutrons and associated detectors to measure the secondary emission of gamma rays.

[1] Applicant respectfully notes that the Examiner appears to have transposed the numbers 8 and 9 in the patent number. The Examiner listed Gozani as being U.S. Patent No. 5,089,640 to Bockmann. The correct patent number for Gozani is 5,098,640.

Furthermore, Gozani does not teach or suggest the use of "*a collimated detector array to receive radiation energy in the form of neutrons emitted from the neutron source*". Instead it discloses at lines 12 to 20 of column 8 "at least one neutron detector positioned on the side of the object being irradiated .... Such neutron detector advantageously measures those neutrons that pass through the object thus providing an indication of the density of the atomic nuclei of the material though which the neutrons have passed".

For these reasons, claim 1 is not anticipated and therefore is patentable over Gozani. It is respectfully submitted that the remaining claims are patentable, at least, based on their dependences.

Sowerby

Claims 1, 2, 22, 24, and 26 stand rejected under 35 U.S.C. § 102(b) as allegedly being anticipated by U.S. Patent No. 4,314,155 to Sowerby. Applicant respectfully traverses this rejection.

Claim 1 recites "*a detector array comprising a multiplicity of individual scintillator pixels to receive neutron radiation and X-ray or gamma-ray radiation emitted from the respective sources and to convert the received radiation into light pulses...*". Sowerby does not teach or suggest this feature.

Moreover, claim 1 recites the feature of "*a collimating block surrounding the neutron and X-ray or gamma-ray sources, comprising one or more slots for emitting substantially fan-shaped radiation beams*". The Examiner maintains that this feature is disclosed by Sowerby at column 4, lines 51 to 59 and column 3, lines 60 to 66. However, at column 3, lines 60 to 66,

Sowerby merely discusses that a shield means may be placed between the sources and the detectors. Thus, even assuming the shield means served as a collimator (which the Applicant maintains that it does not), the shield means does not surround both sources, as set forth by the claim. Moreover, the shield means in Sowerby does not shape the beam in any way. At column 4, lines 51 to 59, Sowerby mentions, in general terms, collimating the neutron and or gamma ray beams. However, the context of this statement is in using two separate backscatter gauges (see column 4, lines 45 to 50). Thus, Sowerby does not disclose a collimator block surrounding both sources, as set forth by the claim.

Furthermore, Sowerby does not teach or suggest the use of radiographic equipment for imaging, that is, Sowerby does not teach '*display means for displaying images based on the mass distribution and the composition of the object being scanned*".

For these reasons, at least, claim 1 is not anticipated and therefore is patentable over Sowerby. It is respectfully submitted that the remaining claims are patentable, at least, based on their dependences.

Claim rejections -- 35 U.S.C. § 103

Gozani/Armistead

Claims 5 and 6 stand rejected under 35 U.S.C. § 103(a) as allegedly being unpatentable over Gozani in view of U.S. Patent No. 5,838,759 to Armistead. Applicant respectfully traverses this rejection.

In order to provide a *prima facie* showing of obviousness under 35 U.S.C 103(a), all the claim limitations must be taught or suggested by the prior art. See, e.g,. *In re Royka, 490.F. 2d 981,180 U.S.P.Q 580 (CCPA 1974); MPEP 2143.03.*

Claims 5 and 6 each depend from claim 1, which has been shown above to be patentable over Gozani. Armistead does not cure the deficiencies of Gozani noted above, because Armistead does not disclose:

(1) "*a first neutron source of substantially mono-energetic fast neutrons produced via the deuterium-tritium or deuterium-deuterium fusion reactions, comprising a sealed-tube or similar generator for producing the neutrons; and a separate source of X-rays or gamma-rays of sufficient energy to substantially penetrate an object to be imaged*" or

(2) "*a detector array ... to receive neutron radiation and X-ray or gamma-ray radiation emitted from the respective sources ... the detector array aligned with the fan-shaped radiation beams emitted from the source collimator and collimated to substantially prevent radiation other than that directly transmitted from each of the sources from reaching the array*".

In contrast, Armisted merely shows an X-ray source 14 which is able to be temporarily converted into a neutron source using a Be converter to produce a pulsed beam of photo-neutrons and gamma-ray detectors 24 disposed to sample the secondary emission of gamma rays. Furthermore, in order to mitigate the absorption of X-rays, the placement of these detectors is disclosed as being placed out of the direct X-ray beam" (see lines 21 to 31 of column 6). Therefore, claims 5 and 6, for this reason at least, are patentable over the cited combination.

Bartle / Armistead

Claims 11, 13, and 23 stand rejected under 35 U.S.C. § 103(a) as allegedly being unpatentable over Bartle in view of Armistead. Applicant respectfully traverses this rejection.

Claims 11, 13 and 23 each depend from claim 1, which has been shown above to be patentable over Bartle. Armistead does not cure the deficiencies of Bartle noted above because Armistead does not disclose:

(1) "*a first neutron source of substantially mono-energetic fast neutrons produced via the deuterium-tritium or deuterium-deuterium fusion reactions, comprising a sealed-tube or similar generator for producing the neutrons.*" or

(2) "*a collimating block surrounding the neutron and X-ray or gamma-ray sources, comprising one or more slots for emitting substantially fan-shaped radiation beams*".

In contrast, Armisted merely shows an X-ray source 14 which is able to be temporarily converted into a neutron source using a Be converter to produce a pulsed beam of photo-neutrons and gamma-ray detectors 24 disposed to sample the secondary emission of gamma rays.

Therefore, claims 11, 13, and 23 are patentable over the cited combination, at least for this reason.

Bartle / Givens

Claims 8-10 stand rejected under 35 U.S.C. § 103(a) as allegedly being unpatentable over Bartle in view of U.S. Patent No. 4,066,892 to Givens. Applicant respectfully traverses this rejection.

Givens does not teach:

(1) "*a first neutron source of substantially mono-energetic fast neutrons produced via the deuterium-tritium or deuterium-deuterium fusion reactions, comprising a sealed-tube or similar generator for producing the neutrons.*"

In contrast, Givens teaches a first neutron source 11, preferably an americium-beryllium (Am^{241}-Be) source which produces gamma rays by way of inelastic scattering, and a second neutron source 12, preferably californium (Cf^{252}) to produce 4.43-Mev gamma rays by way of inelastic scattering.

Moreover, Givens contains no relevant teachings concerning:

(2) "*a collimating block surrounding the neutron and X-ray or gamma-ray sources, comprising one or more slots for emitting substantially fan-shaped radiation beams.*"

In fact a collimator is not necessary or desirable in Givens because the device of Givens is dropped down into a coal-bearing zone in the earth.

In addition Givens does not disclose the feature of

(3) "*a detector array comprising a multiplicity of individual scintillator pixels to receive radiation energy emitted from the sources*". Therefore claims 8 to 10 are patentable over the cited combination.

Bartle / Katagiri

Claim 12 stands rejected under 35 U.S.C. § 103(a) as allegedly being unpatentable over Bartle in view of U.S. Patent Application Publication No. 2002/0121604 to Katagiri. Applicant respectfully traverses this rejection.

Claim 12 depends from claim 1, which has been shown above to be patentable over Bartle. Katagiri does not cure the deficiencies of Bartle noted above, because Katagiriis directed to neutron image detectors per se. Therefore, claim 12 is patentable over the Bartle and Katagiri combination.

Bartle / Armistead / Walterman

Claim 14 stands rejected under 35 U.S.C. § 103(a) as allegedly being unpatentable over Bartle in view of Armistead in view of U.S. Patent No. 6,061,469 to Walterman. Applicant respectfully traverses this rejection.

Claim 14 depends from claim 1, which has been shown above to be patentable over the Bartle and Armistead combination. Walterman does not cure the deficiencies of the Bartle and Armistead combination noted above, because Walterman is merely directed to a method of rendering x-ray like images. Walterman does not teach nor suggest:

(1) "*a first neutron source of substantially mono-energetic fast neutrons produced via the deuterium-tritium or deuterium-deuterium fusion reactions, comprising a sealed-tube or similar generator for producing the neutrons.*" or

(2) "*a collimating block surrounding the neutron and X-ray or gamma-ray sources, comprising one or more slots for emitting substantially fan-shaped radiation beams*". Therefore claim 14 is patentable over the cited combination.

Bartle / Walterman

Claims 16, 19, and 21 stand rejected under 35 U.S.C. § 103(a) as allegedly being unpatentable over Bartle in view of Walterman. Applicant respectfully traverses this rejection.

Claims 16, 19, and 21 each depend from claim 1, which has been shown above to be patentable over Bartle. Walterman does not cure the deficiencies of Bartle, because Walterman is directed to a method of rendering x-ray like images per se. Therefore, claims 16, 19, and 21 are patentable over the Bartle and Walterman combination.

Bartle / Eberhard

Claim 25 stands rejected under 35 U.S.C. § 103(a) as allegedly being unpatentable over Bartle in view of U.S. Patent No. 5,905,806 to Eberhard. Applicant respectfully traverses this rejection.

Claim 25 depends from claim 1, which has been shown above to be patentable over Bartle. Eberhard does not cure the deficiencies of Bartle, because Eberhard is merely directed to computational methods. Eberhard does not disclose:

(1) "*a first neutron source of substantially mono-energetic fast neutrons produced via the deuterium-tritium or deuterium-deuterium fusion reactions, comprising a sealed-tube or similar generator for producing the neutrons.*" or

(2) "*a collimating block surrounding the neutron and X-ray or gamma-ray sources, comprising one or more slots for emitting substantially fan-shaped radiation beams*".

Applicant respectfully notes that Eberhard merely makes a passing reference to the use of an additional inspection method such as pulsed fast neutron analysis to verify the presence or absence of an explosive.

Therefore, claim 25 is patentable over the Bartle and Eberhard combination.

Bartle / Homme

Claim 27 stands rejected under 35 U.S.C. § 103(a) as allegedly being unpatentable over Bartle in view of U.S. Patent Application Publication No. 2003/0116715 to Homme. Applicant respectfully traverses this rejection.

Claim 27 depends from claim 1, which has been shown above to be patentable over Bartle. Homme is merely directed to a radiation detector and more specifically to a dental radiation detector and does not make up for the deficiencies of Bartle. Therefore, claim 27 is patentable over the Bartle and Homme combination.

Conclusion

In view of the above, reconsideration and allowance of this application are now believed to be in order, and such actions are hereby solicited. If any points remain in issue which the Examiner feels may be best resolved through a personal or telephone interview, the Examiner is kindly requested to contact the undersigned at the telephone number listed below.

The USPTO is directed and authorized to charge all required fees, except for the Issue Fee and the Publication Fee, to Deposit Account No. 19-4880. Please also credit any overpayments to said Deposit Account.

Respectfully submitted,

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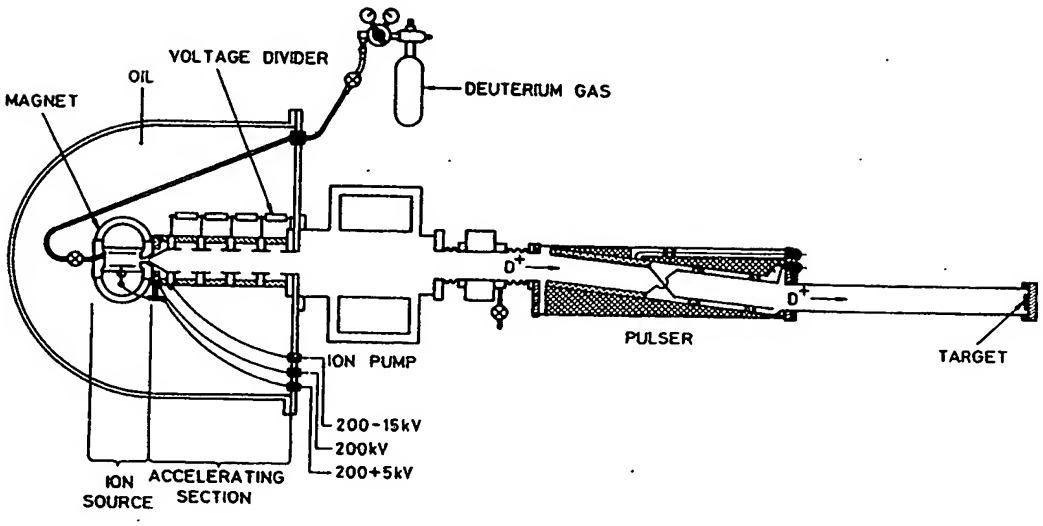

FIGURE 89. Schematic diagram of a compact microsecond-pulsed neutron generator.

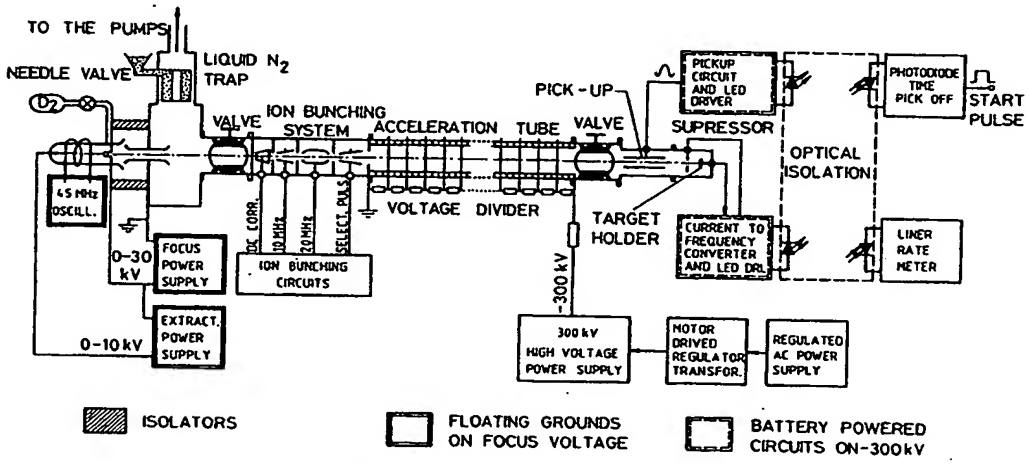

FIGURE 90. Physical layout of a nanosecond-pulsed neutron generator. (After Sztaricskai, T., Vasvary, L., and Pető, G., ZfK-324, Dresden, D. D. R., 1976, 218.)

Sealed tubes have advantages in some respects, e.g., they are an inexpensive, portable source of neutrons with small dimensions and are easy to operate. The generator consists of an ion source, accelerating structure, target section, and a replenisher sealed inside a glass tube. The ion source is usually a Penning-type with a small permanent magnet. The tube operates at 100 to 200 kV within a pressure range extending from 10^{-2} to 2 Pa, which was maintained in the tube by the use of a deuterium-impregnated zirconium wire spiralized around a tungsten wire or titanium powder. Deuterium gas is released by a layer deposited on the surface of a nickel cylinder. Deuterium gas is released by varying the temperature of the absorber. Without using a replenisher, the discharge would exhaust the initial deuterium gas within a short time. The life of neutron tubes can be increased by using a replenisher filled with 50% deuterium and 50% tritium. Therefore, during operation, a drive-in target is produced by the mixed beam. The lifetime of the tubes is a few hundred hours, depending

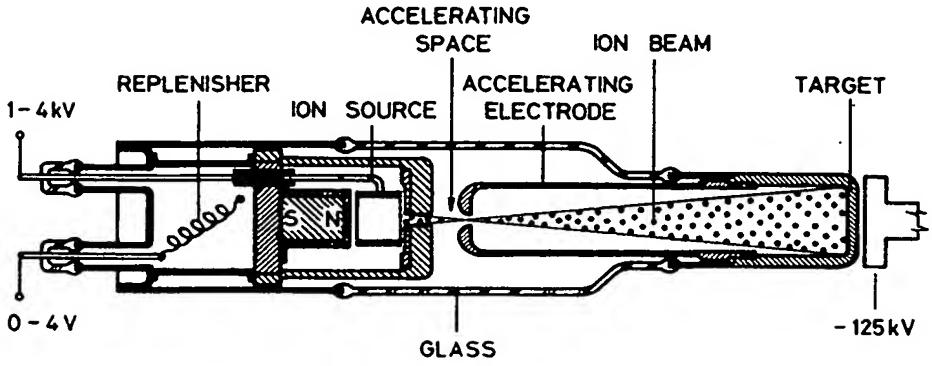

FIGURE 91. Scheme of a sealed tube with Penning source. (After Reifenschweiler, O., *Philips Res. Rep.*, 16, 401, 1961. With permission.)

on the operating conditions. Sealed tubes with a pulse length from 10 ns to 0.2 s and repetition rates from 1 to 10^5 Hz, with an output of about 10^8 n per pulse, are commercially available. The physical dimensions range from 6 to 40 cm in diameter and 100—170 cm in length. A sealed-off neutron generator with a Penning-type ion source is shown in Figure 91. A schematic diagram of a sealed tube developed by Schmidt and Dohrmann[242] that produces 5×10^{12} n/s in continuous operation, using mixed beam of D and T from a toroidal ion source to bombard a central conical target in a radial magnetic field, is presented in Figure 92. The target consists of scandium in which a mixture of D and T of about 2×10^{13} Bq was absorbed. The operating pressure is 6×10^{-2} Pa at 200 kV accelerator voltage. A high-intensity sealed neutron generator manufactured by Cyclotron Corporation is capable of producing a source strength of 8×10^{12} n/s during 500 h of operation. Ion beams from four DP sources are accelerated in a 1 cm gap by 175 kV. A uranium trap is used as a gas replenisher, which contains 7.5×10^{13} Bq tritium and an equal number of deuterium atoms. Some characteristics of neutron generators are summarized in Table 21.

VII. NEUTRON FLUX AND YIELD MEASUREMENTS

For D-D and D-T reactions, the neutron flux can be measured to an absolute accuracy of about 1% using the associated particle method (APM).[246-249] By detecting the associated particle within a well-defined recoil solid angle, the neutron flux can be determined in the respective solid angle and — with a knowledge of the angular distribution — the total yield of the source as well. Observing the coincidences between the associated particle detector and a neutron detector, the neutron beam can be collimated (electronic collimation)[250] and the efficiency of the monitoring neutron detector and the neutron spectrum can be determined. In the case of D-D reaction, the separation of ^{3}He, ^{3}H, and scattered deuterons is difficult;[72] therefore, knowing the ratio of the cross-section[251] of the D(d,n)^{3}He reaction to that of D(d,p) ^{3}H, the measurement of neutron flux is performed by detecting the protons, which can be easily separated. Pulse height spectra,[252,253] obtained by a thin (~5 mg/cm^2) CsI(Tl) associated particle detector for TiT and TiD targets, are shown in Figure 93. Using a thick (~0.1 mm) CsI(Tl) detector, the proton pulses are considerably higher than those from ^{2}H, ^{3}He, ^{3}H, and alpha particles. Consequently, they can be easily discriminated from the background. Semiconductors can also be successfully applied as associated particle detectors.[254]

A geometrical arrangement for the measurements of neutron flux distributions in a moderator surrounding the D-T target, using an APM monitor, is shown in Figure 94. Technical data of the APM system are as follows: source-detector distance, 71 cm; diameter of the

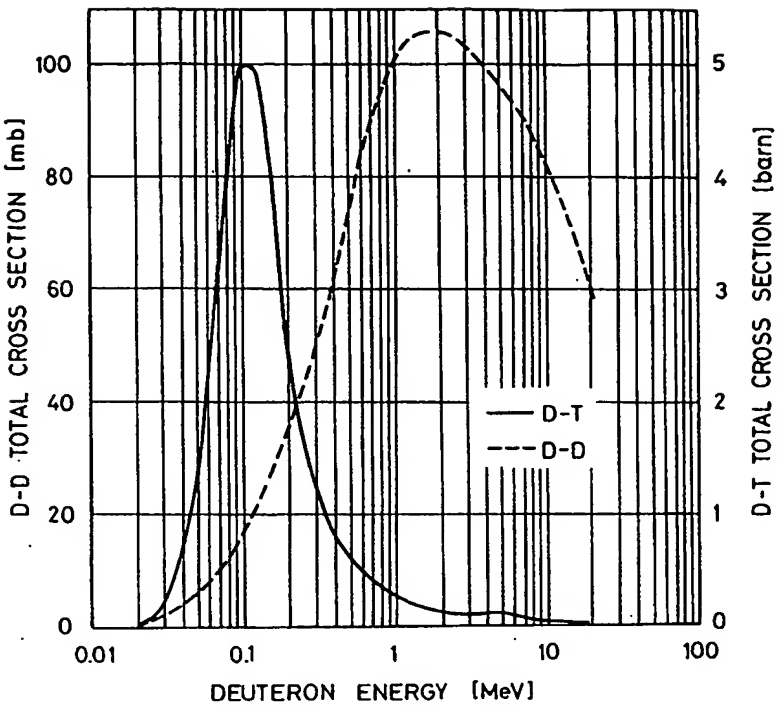

FIGURE 2. Energy dependence of the total cross-section for the $^{2}H(d,n)^{3}He$ and $^{3}H(d,n)^{4}He$ reactions.

where E_d is in keV. Accurate data are needed for the total and differential cross-sections for the D-D and D-T reactions below 10 keV to the design of fusion reactors.

There are a number of measurements for the differential cross-sections of the D-D and D-T reactions as a function of deuteron energy. Measurements were carried out by the following methods: associated-particle method (APM), neutron counter telescope (NCT), time-of-flight (TOF), activation foil detector (AFD), stilbene scintillation detector (SSD), long counter (LC), fission fragment detector (FFD). Principles of these techniques and the comparison of various methods are described in References 16 and 19. There are technical difficulties, especially in the case of the APM method, in detecting the neutrons at large angles. This problem can be solved by interchanging the projectile and target nuclei, using the inverse reaction. In such cases, the backward and forward angles change places. Therefore, the energy of projectile should be changed to assure the same center-of-mass energy. For example, in the case of the most commonly used $^{3}H(d,n)^{4}He$ reaction, the triton energy must be 1.5 times that of the deuteron.

B. Angular Distribution of D-D and D-T Source Yields

Many experimenters have pointed out that the measured angular distributions can be well fitted with Legendre polynomials. On the basis of the available thin target experimental data, Liskien and Paulsen[15] calculated the laboratory differential and total cross-sections as a function of deuteron energy from 20 keV to 10 MeV for D-D and D-T reactions. For parametrization of the differential center-of-mass cross-sections, the following form can be used:

A Review of NEUTRON BASED NON-INTRUSIVE INSPECTION TECHNIQUES

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Abstract

Non-intrusive inspection of large objects such as trucks, sea-going shipping containers, air cargo containers and pallets is gaining attention as a vital tool in combating terrorism, drug smuggling and other violation of international and national transportation and Customs laws. The importance of reliable, accurate and rapid inspection at all ports of entry: sea, land and air has been underscored by the events of September 11 2001.

Neutrons are the preferred probing radiation when material specificity is required, which is most often the case. Great strides have been made in neutron based inspection techniques. Fast and thermal neutrons, whether in steady state or in microsecond, or even nanosecond pulses are being employed to interrogate, at high speeds, for explosives, drugs, chemical agents, and nuclear and many other smuggled materials. Existing neutron techniques are compared and discussed.

Introduction

Effective inspection of objects of all sizes, from a small postal parcel to large containers and trucks, for explosives, narcotics and other controlled substances is essential for the success of counter-terrorism efforts. The magnitude of the problem is exemplified by the fact that a significant fraction (~70%) of all drugs are smuggled into the U.S.A. through trucks crossing the southern borders. The fatal results of explosions on aircrafts from relatively small explosives smuggled on board airplanes via check-in or carry-on luggage are also well known.

Successful efforts to combat this type of terrorism and drug supply require efficient, rapid and cost-effective inspection techniques of objects of all sizes. Until recently, the techniques used to thoroughly inspect various size objects were either material non-specific, such as x-ray or manual. The latter, even when considered reliable, is highly labor intensive and can hardly be expanded to meet the challenge of abating the flow of drugs or intercepting the rarer events of explosives in containers or luggage. Hence the only way to achieve the goal of national counter-terrorism and counter-drug interdiction is to employ rapid, automatic, non-intrusive technology to inspect cargo shipments or parcels and luggage without removing the contents for manual or non-specific x-ray inspection.

Nuclear techniques are uniquely suited to be the core of effective inspection systems. They have the essential capabilities required to do the job, including high penetrability, specificity, and speed. They are inherently non-intrusive, and the data they generate is amenable to advanced data analysis techniques and automatic decision making. Each capability by itself is meritorious; properly applied together, they provide an hitherto unmatched ability to inspect objects. However simply possessing these good attributes is a necessary but not sufficient condition for producing an effective inspection system. To develop successful inspection systems the requirements dictated by a specific or range of applications must be considered from the very beginning of the development program.

During the last decade, great strides were made in research, development, construction and partial deployment of nuclear based techniques for explosive and other contraband detection. Only a few of these techniques, such as the neutron based ones, led or can lead to a practical and efficient inspection system.

Following a brief discussion of properties of various substances that make them detectable by nuclear techniques, the principles of the various techniques are touched upon and their actual or potential application for large[1] objects (cargo containers or trucks) will be evaluated and described.

Material and Elemental Features

Nuclear techniques detect the presence of the material of interest by detecting specific isotopic nuclei through their unique

[1] Applications of nuclear techniques to smaller containers such as luggage are discussed in many publications (e.g., ref. 1).

nuclear structures. The key elemental features that allow the detection of some important materials, for which nuclear detection is applied, are given in abbreviated form in Table 1.

The elemental densities of hydrogen, chlorine and nitrogen are measured by the thermal neutron capture (n,) process. Chlorine forms the basis for the detection of hydrochlorinated cocaine and heroin. Nitrogen detection forms the basis of detection of nitrogen rich explosives. More specific detection of these contraband is achieved by measuring more of the elemental constituents, namely oxygen, carbon, nitrogen, chlorine and hydrogen. The first four elements are detected by the characteristic gamma rays emitted when fast neutrons are inelastically scattered by the nuclei of the elements. Indeed oxygen can only be detected by this process, while carbon is detected more efficiently by the same process. Nitrogen and chlorine can also be detected through the fast neutron inelastic scattering (n,n ,) process, but with lower energy characteristic gamma rays compared to the (n,) process. Fissionable materials are detected, obviously, by the products of the fission process. The elemental densities in minerals is determined mainly by the characteristic gamma rays emitted following the radiative capture of thermal neutrons.

Table 1: Key Elemental Features and Signatures

Material	Key Elemental Features	Usable Nuclear Reactions	Available Signatures
CONTRABAND Explosives	Elemental Density (g/cc) relatively high O relatively high N relatively low C relatively low H	 (n,n) (n_{th},) and (n,n) (n,n) (n_{th},)	 6.130 MeV 10.80, 5.11, 2.31, 1.64 MeV 4.43 MeV 2.223 MeV
Drugs (Cocaine/Heroin)	relatively high C relatively high H relatively low O low-medium Cl (for HCl-drugs)	(n,n) (n_{th},) (n,n) (n_{th},) and (n,n)	as above as above as above 6.110 MeV and other strong lines for Cl
MINERALS Cement	Ca, Si, Fe, Al, Mg	(n_{th},)	specific capture -rays, e.g., 6.420 MeV for Ca 4.934 MeV for Si 7.630/46 MeV for Fe, etc.
Coal	C (high concentration) H, S, Si, Al, Fe, Ca, K, Na, Ti	(n_{th},), (n,n) (n_{th},)	specific capture (or inelastic) -rays, e.g., 4.945 MeV (n,) and 4.43 MeV (n,n) for C, 2.223 MeV for H, 5.420 MeV for S, etc.
NUCLEAR	^{232}Th, ^{233}U, ^{235}U, ^{239}Pu, ^{240}Pu	(n_{th},f), (n_ff), (,f) secondary; (n_{th},), (n,n)	n_p, n_d, $_p$, $_d$; total/coincidence; very high density

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The Need for Nuclear Imaging

Illicit substances are generally similar in their physical appearance to most benign materials one encounters in daily life. Some, like military high explosives (C4, PETN, Semtex) and TNT, are somewhat denser than others. However many other powerful explosives have significantly lower densities, similar to many common plastics and liquid substances. Narcotics span a wide range of densities, up to that of water. All these substances can be molded to any form, eliminating their recognition by shape, the most commonly used feature in x-ray inspections.

As discussed in the previous section, contraband materials however, have unique chemical and hence, elemental

compositions which are generally very different from other substances. The ability to measure precisely elemental concentrations in an inspected object is absolutely necessary but far from sufficient for a successful inspection system. This stems from the fact that the key elements present in illicit materials of interest, i.e., C, N, O, H, and Cl, are present in almost all common materials. Unmistaken presence of the right concentrations and combinations of these elements, characteristic to contraband, is the needed proof. If the measurement is localized, the determined elemental densities will represent the material composition at that very volume element (voxel) and not an average over a larger volume. The latter may dilute the information and the unique composition of the concealed substance will be lost, resulting in a failure to detect. Thus the objective of an effective contraband inspection system has to be the determination of relevant elemental density *spatial* distribution in the inspected object. This multi-elemental "mapping" is the necessary "imaging" capability afforded by nuclear techniques.

The ability to measure individual elements is crucial to the success of an inspection technique. Indeed, the more elements a technique can determine, the better will be its ability to distinguish between benign and illicit materials. While nitrogen density is a good indicator of explosives, the combination of low oxygen *(and* possibly low nitrogen) and high carbon densities, or exceptionally high carbon/oxygen ratio, are strong indications of a presence of drugs.

While imaging is not a feature commonly associated with nuclear techniques, it is essential to the ability to distinguish, with high selectivity, the contraband from the overwhelming majority of benign substances surrounding it. This is the reason why the imaging feature is highlighted in the next section, which briefly discusses possible nuclear techniques for contraband detection.

Possible Nuclear Techniques for Contraband Detection

Excluding techniques that require nuclear reactors or large high energy (e.g., >50 MeV electron) accelerators, one can identify nine nuclear based techniques (Table 2). The listed techniques are currently at various levels of development, from a very early stage of conceptual design to operational status (e.g., TNA). Some of the techniques have compelling technical and operational merits. Others may be no more than interesting exercises in applied nuclear physics. The very concise description of each technique commences with its technical name (mostly an acronym), the probing radiation used; the main nuclear reaction taking place that creates the elemental signal of interest; the detected radiation; possible sources for the probing radiation; the primary and secondary signatures; the imaging capabilities of the technique and finally a few comments addressing key issues or limitations.

The table shows a diversity of nuclear techniques that may be relevant to the problem of cargo inspection. The techniques are described in more detail in the cited references but some general observations can be made. Each technique has its own intrinsic merits and limitations. When these attributes are applied to a suitable problem, a good solution can be achieved. TNA (and probably GTNA and FNA) are demonstrably applicable to explosive and drug detection in small packages and luggage. In fact the TNA Explosive Detection System (EDS) inspected more than a million passenger bags at airports in the U.S.A. and abroad between 1989 to 1994. They are however, not usable for large container inspection. This stems from the fact that thermal neutrons do not have sufficient penetration to probe an entire container. The attenuated thermal flux will greatly vary within the container depending on its contents. Thus it is very difficult to reconstruct the elemental distribution even if some gamma-rays are detected by the surrounding detectors. Though the attenuation of the probing neutrons is improved in the FNA technique, the imaging capabilities are still very poor. This is the result of the fact that most of the container's inside volume is far from the surrounding detectors. Hence there are many volume elements (voxels) which are at about the same distance from the detectors, yielding no spatial information.

Some of the other techniques inherently provide two dimensional images, i.e., they provide good two dimensional projection of the three dimensional object they measure. X-rays, for example, measure physical density with excellent resolution. The neutron resonance attenuation (NRA) technique determines, under some conditions, the elemental areal density of carbon, nitrogen, oxygen and hydrogen. The gamma resonance attenuation (GRA) technique using a very high current accelerator can, in principle, determine with a good spatial resolution the nitrogen areal density along the beam path. In order to convert a projection measurement such as x-ray, GRA and NRA into a three dimensional image, some kind of tomography must be done. This involves repeated measurements of the object with the interrogation beam projected from different angles. Many measurements (at least three different beam angles) must be made of each volume element (voxel) in order to uniquely reconstruct the volume. The computation of the statistical estimation error for a single voxel is complex and greatly depends on the techniques being used. For some simple cases, if the measurement time and/or the intensity of the probing radiation

increases as the square root of the number of pixels in a slice, then the error for each voxel will be comparable with the error of a single measurement. This puts a great demand on the individual techniques which may be already close to their performance limit in providing a two dimensional image of a large container. Furthermore, the effort needed to perform a tomographic reconstruction of a 10-18 meter long, 2 meter high and 2.5 meter wide container are nothing less than herculean. It might be far better to find, if necessary and possible, a beneficial use for these techniques in their two dimensional mode to enhance other more direct three dimensional image techniques.

Direct imaging is provided by PFNA (nanosecond Pulsed Fast Neutron Analysis) and API (Associated Particle Imaging). The latter, based on 14 MeV neutrons is destined to have poor signal to background, limited to low intensity, requiring a long measurement time, which precludes routine container inspection. PFNA provides a three dimensional distribution of the key elements present inside the container. The quality of the image does not depend on the detector-voxel distance, except indirectly through the counting statistics. The ability to obtain clean elemental signals and a good spatial resolution make the PFNA a most unique and powerful tool for cargo inspection.

A qualitative assessment of the nuclear based techniques discussed above are summarized in the form of advantages and disadvantages in Table 3. The x-ray radiography technique, using high energy is listed also as a point of reference. This technique is being employed for large containers mainly because of users' familiarity with the x-ray radiography concept and high penetrability, even though no material-specific information is expected or obtained.

Table 3: Qualitative Assessment of Nuclear Based Cargo Inspection Systems

#	Technique	Advantages	Disadvantages
1	TNA	Most studied, well understood, relatively low cost, applicable to package size objects; readily available. Good sensitivity to N and Cl. The only nuclear technique which can use radioisotopic neutron source.	Inapplicable to large container inspection because of neutron attenuation, poor imaging for large objects.
2	GTNA	Lower background in the detectors from the source and lower energy neutrons because of the time delay; accelerator available, but needs some development.	As above, plus: intensity during the pulse much higher than in #1, resulting increased pile-up effects, leading to possibly lower sensitivity compared to #1.
3	FNA	Good penetration; multiple elemental signature; lowest cost among fast neutron interrogation concepts; accelerator available (14 MeV ENG). Applicable to empty or lightly loaded vehicles and tanker trucks.	Elemental sensitivity lower than PFNA, great difficulty in applying to large containers because of very poor image, large source induced background in detectors; accelerator needs improvement in reliability.
4	FNA/ GTNA	As in #2 and #3.	As in #2 and #3. Cannot optimize system simultaneously for both GTNA and FNA.
5	PFNA	Highly applicable to all size containers, highest elemental sensitivities, highest detector signal/background ratio; lowest interference effects, direct 3-dimensional imaging resulting in highest possible detection with the lowest false alarm probability. Expandable to include many elements; accelerator available.	More complex, may require more room and is relatively more expensive than the techniques above; reduced sensitivity for large dense hydrogenous contents. Requires nsec pulsed 6 MV d-accelerator with improved reliability.
6	API	Multiple elements, relatively low cost, small and light; direct crude imaging.	Inherently poor signal to background, very low intensity, very long measurement time, inapplicable to routine container inspection; accelerator and related auxiliary equipment need further development.

7	NRA	Highest elemental cross-section among nuclear resonance based techniques, multiple organic element determination (H, C, N, O); accelerator available.	Two dimensional projection (like x-rays); complex and unproven methods to get 3-D imaging. Requires intense nsec pulsed accelerator for "white" neutron spectrum. Signal highly attenuated even for low density hydrogenous contents. Not applicable for large containers.
8	GRA	No neutrons used (considered by some as important). Good transmission through hydrogenous medium.	Single elemental determination (N), 2-D projection; requires accelerator with extremely high current and appropriate ^{13}C target to handle it. Not applicable for large containers.
9	High Energy X-ray	High transmission through hydrogenous medium. High resolution 2-D images. A few systems already installed.	Not material/elemental specific. Only 2-D imaging. Human decision based on shapes, whereas drugs and explosives can be molded in any shape.

Conclusions

Nuclear based techniques offer unique capabilities vital for non-intrusive inspection of both small and large objects for contraband, including explosives and drugs. A broad range of possibly relevant techniques were briefly reviewed in this paper. The neutron based techniques are shown to be the most versatile. These techniques span the range from being single element specific, with emission tomography-type imaging (TNA), to multiple element and fully direct imaging with time of flight technique (PFNA). A broad range of applications is possible with the techniques (see Table 4). A few of them have been implemented or are being seriously investigated for this purpose.

Table 4: Threats and Applicable Technologies

Threat	Location	Nuclear Technology (and supporting Technologies)
Explosives, drugs and nuclear material in luggage and parcels (high throughput required)	Airport, post office, border inspections	TNA with imaging (dual energy x-ray, vapor/particulates sensors, dogs)
Explosives and drugs in small items: laptop computers, electronics, briefcases (low throughput acceptable)	Courthouses, government and corporate headquarters, airport lobbies	TNA (x-ray, "sniffers")
Buried anti-vehicular and anti-personnel mines	Overseas: Indochina, Bosnia, Europe, Africa, etc., military base cleanup.	TNA (confirms or clears detections by metal detector or ground penetrating radar)
Unexploded ordnance (UXO)– conventional or chemical	As above	As above
Explosives and/or drugs in lightly loaded vehicles	Border inspections, parking garages, parked cars and entrance to sensitive facilities	TNA (vapor/particulates sensors, dogs, isotopic gamma source radiography)
Explosives, drugs, environmentally hazardous materials, smuggled dutiable goods, nuclear material in trucks, containers, air cargo	Customs inspection at land and sea ports of entry, air cargo, entrance to sensitive facilities	PFNA (high-energy x-ray, vapor/particulates, dogs)

Nuclear and hazardous chemical ("mixed") wastes in 55 gal drums or larger boxes	Nuclear reprocessing plant, facilities in the nuclear fuel cycle, clean up of previous nuclear sites	PFNA and TNA

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GLOSSARY OF NUCLEAR TECHNIQUES

TNA - Thermal Neutron Analysis
Method based on the capture of thermal neutrons by nuclei creating high energy gamma rays which are characteristic to the specific nuclei. Thermal neutrons are produced by slowing down fast neutrons from isotopic sources or accelerators in a specially designed moderator and in the interrogated object itself. The gamma rays are detected by an array of detectors surrounding the object. Spatial information on the interacting nuclei of interest (e.g., nitrogen, chlorine, etc.), to determine if they are present, for example, in a lump or sheet form, is obtained from the detector array. Configurations with source, moderator and detectors on the same side ("single-sided" TNA) are possible and were found useful.

GTNA - Gated Thermal Neutron Analysis
A TNA like technique, but with a neutron source which is periodically on for a small fraction of time (e.g., 10 s pulses 1000 to 5000 times a second). The gamma rays are measured after the source is shut off. The time dependence of the capture gamma rays follows the time decay of the thermal neutron population, normally called neutron die-away. The gamma rays and the decaying neutron population can be measured.

FNA - Fast Neutron Analysis
Method based on the fast neutron interactions, mostly inelastic neutron scattering, with the nuclei of interest. Characteristic gamma rays form nitrogen, carbon, oxygen, chlorine and other elements can be measured. An array of gamma ray detectors surrounds the object to yield spatial distribution of the elements of interest similar to TNA. Neutrons are usually generated by a 14 MeV electronic neutron generator.

FNA/GTNA
Combination of GTNA with FNA. The latter is done when the source is on and the former when the source if off.

PFNA - Pulsed Fast Neutron Analysis
Method based on fast neutron interactions to yield characteristic gamma rays, similar to FNA. The technique employs the nanosecond Time of Flight (TOF) technique to obtain the spatial distribution of the signal. The TOF is achieved by using very narrow, about 1 ns pulses of monoenergetic neutrons with a frequency of 5 to 10 MHZ.

API - Associated Particle Imaging
A technique to tag the source neutrons, in time and direction, by the associated charged particle emitted simultaneously in the nuclear reaction that generated the neutrons, e.g., He (particle) and He in the (D,T) and (D,D) neutron producing reactions respectively.

NRA - Neutron Resonance Attenuation
A technique to measure the areal density (density x thickness) of elements present in the interrogated object. The technique takes advantage of sharp resonances and other features in the neutron total cross-section in the energy range of 0.5 to 5 MeV. Two dimensional projection of the areal density of N, C, O, and H can be obtained using fast neutrons with a broad energy spectrum, generated in narrow pulses, to perform TOF energy measurements.

NES - Neutron Elastic Scattering
A technique to measure elemental concentration using the different structures of the cross-sections of the neutron elastic scattering in the various elements of interest, similar to the NRA technique. In the NES the scattered (mostly in backward angles) neutrons are measured.

GRA - Gamma Resonance Attenuation
The principle of GRA uses the ability of certain isotopic nuclei (most notably, ^{14}N) to selectively absorb gamma rays of specific, precisely defined energy. The specific gamma rays are said to be in resonance with a nuclear level of the elemental nuclei of interest. The resonant gamma rays are also absorbed in a non-resonant way in all the materials present. The GRA can provide a two dimensional projection of the (areal) density of the element of interest.

Photo-Nuclear Activation
A technique whereby specific nuclei (e.g., ^{14}N) are selectively made radioactive by a photo-nuclear reaction. The measurement of the induced radioactivity (mainly 0.511 MeV gamma rays) indicates the presence of an element of interest. Spatial distribution of the activation can, in principle, be determined by the Positron Emission Tomography (PET)

technology.

Table 2: Basic Facts on Nuclear Techniques with Some Relevance to Cargo Inspection

#	Technique* and Ref. #	Probing Radiation	Main Nucl. Reaction	Detected Radiation	Sources	Primary/ Secondary Signatures	Imaging Capabilities	Comments
1	TNA 1	Thermalized neutrons	(n,)	Neutron capture -rays	^{252}Cf, also accel. based sources: (D,D), (D,T), (D,Be), (P,Li), (P,Be), etc.	Cl, N H, Metals	Fair for small, very poor for large objects	Limited view detectors improve imaging, requires stronger source
2	GTNA 2	Time dependent thermal neutron flux	(n,)	Time dependent capture -rays and neutrons	s pulsed (D,D), (D,T), (D,Be), (P,Li), (P,Be), and others	N, Cl H, Metals	Poor to very poor	Low sensitivity
3	FNA 3	Fast (high energy) neutrons	(n,n)	-rays produced from inelastically scattered neutrons	(D,T)	O, C, N H, Cl	Same as #1	Limited view detectors improve imaging, requires stronger source; source induced detector background
4	FNA + GTNA 2	Fast neutrons during the pulse, then like #2	(n,n) + (n,)	Like GTNA and FNA	s pulsed (D,T), accel. source	O, C, N H, Cl	Same as #1	Low sensitivity; see also comments on #3
5	PFNA 4	Nanosecond (ns) pulses of fast neutrons	(n,n)	Like FNA	ns pulsed (D,D) accel. with E_d ~6 MeV	O, C, N, Cl, Others Metals, Si, Others	Direct 3-D imaging; applicable to small and large objects	Direct imaging; conventional imaging methods further reduce background
6	API 5	14 MeV neut. with assoc. particles	(n,n)	in coincidence with	(D,T)	O, C, N	Fair to good	Direct imaging; long measuring time
7	NRA NES 6	ns pulses of white spectrum, or variable monoenergetic neutrons, E_n < 7 MeV	(n,n) resonance	Scattered or attenuated source neutrons	ns pulsed, (D,Be) white neutron spectrum	O, N, C H	Good in 2-D, questionable for 3-D	Difficult to get 3-D imaging
8	GRA 7	Monoenergetic -rays, 9.17 MeV	(,) resonance	Attenuation of photon beam	High current proton (E_p < 2 MeV), using ^{13}C (p,) reaction	N	Good in 2-D, unproven in 3-D	Requires very high current accelerator, complex mechanism for tomographic irrad.

9	Photo-nuclear Activation 8	> 13 MeV Bremmstrahlung	(,n)	0.511 MeV from + annihilation	High power electron linac	N	Good for small objects, infeasible for large objects	Requires extremely high dose rate, self absorption of signal (.511 MeV) gamma rays, low efficiency, slow

*See Glossary at the end of this paper.